Ocean Winds and Turbulent Air-Sea Fluxes Inferred From Remote Sensing

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1. Introduction

Air-sea turbulent fluxes determine the exchange of momentum, heat, freshwater, and gas between the atmosphere and ocean. These exchange processes are critical to a broad range of research questions spanning length scales from meters to thousands of kilometers and time scales from hours to decades. Examples are discussed (section 2). The estimation of surface turbulent fluxes from satellite is challenging and fraught with considerable errors (section 3); however, recent developments in retrievals (section 3) will greatly reduce these errors. Goals for the future observing system are summarized in section 4.

Surface fluxes are defined as the rate per unit area at which something (e.g., momentum, energy, moisture, or CO_2) is transferred across the air/sea interface. Wind- and buoyancy-driven surface fluxes are called surface turbulent fluxes because the mixing and transport are due to turbulence. Examples of nonturbulent processes are radiative fluxes (e.g., solar radiation) and precipitation (Schmitt et al., 2010). Turbulent fluxes are strongly dependent on wind speed; therefore, observations of wind speed are critical for the calculation of all turbulent surface fluxes. Wind stress, the vertical transport of horizontal momentum, also depends on wind direction. Stress is very important for many ocean processes, including upper ocean currents (Dohan and Maximenko, 2010) and deep ocean currents (Lee et al., 2010). On short time scales, this horizontal transport is usually small compared to surface fluxes. For long-term processes, transport can be very important but again is usually small compared to surface fluxes.

Satellite observations of ocean winds have been used in the estimation of all these fluxes. Wind speed can be measured from individual passive instruments and active instruments. Passive instruments measure electromagnetic energy radiated from the water surface. Wind speed is related to differential emission signatures generated by wind-induced effects on the surface roughness and white capping. There are many passive instruments capable of measuring winds (Bourassa et al., 2010b). Active instruments (e.g., QuikSCAT) detect the surface roughness by sending a pulse of electromagnetic energy to the surface and measuring the fraction that returns to the satellite. Observing the same location from different view angles also allows active sensors to retrieve the wind direction. There are several types of instruments that measure vector winds; scatterometers (Bourassa et al., 2010b) are currently considered to be the most practical satellite instruments. Wind instruments typically measure microwaves, which easily pass through clouds but have some difficulties with accurate retrievals through rain (Draper and Long, 2004; Weissman and Bourassa, 2008).

Sea surface temperatures are also sufficiently well observed for most turbulent surface flux applications (Donlon et al., 2007). In contrast, near-surface atmospheric humidity and temperature have historically been difficult to retrieve via remote sensing methods because of the much larger signal from the ocean surface. There have been considerable improvements (discussed below) in the last decade. One of the great difficulties of atmospheric temperature and humidity observations is they are retrieved with frequencies that are quite sensitive to liquid water (i.e., excessive cloud cover), resulting in a lack of data in many areas that have very active weather and large fluxes.

2. Example Applications and Sampling Issues

a. Applications

Science questions that rely on air-sea turbulent fluxes are myriad, encompassing climate science, tropospheric dynamics, and upper-ocean physics. The specific requirements for air-sea fluxes depend on the scales of the processes under consideration. We cannot hope to inventory all possible applications here, but we highlight a selection to indicate the requirements flux observations need to meet. Most applications require combinations of spatial and temporal sampling, achieved most practically with a satellite-based observing system.

On a planetary scale, air-sea fluxes determine the net oceanic uptake of heat and CO_2, both on a cyclical seasonal scale and as part of a long-term trend resulting from natural and anthropogenically forced low-frequency variability. Air-sea turbulent sensible and latent heat fluxes vary in magnitude through the course of the year, with sensible heat fluxes also changing sign. In most places, the ocean takes up heat during the summer and releases it in winter. Seasonal flux differences are typically about 50 Wm^{-2}. Low-frequency variability is also prominent because of modes of naturally coupled ocean-atmosphere processes such as ENSO. Superimposed on these seasonal and natural cycles is a smaller long-term radiative forcing due to increased anthropogenic heat storage. However, this signal, , estimated to be about 0.85 Wm^{-2} (Hansen et al., 2005), is so small that it defies our existing flux instrumentation. Instead, long-term trapping of heat in the ocean is best monitored by assessing changes in upper-ocean heat content (e.g., Johnson et al., 2006; Levitus et al., 2009).

Understanding the physics behind ocean storage of heat and CO_2 depends on understanding the oceanic mixed layer. The ocean mixed layer is typically represented as a homogeneous layer of water at the top of the ocean that readily communicates with the atmosphere (Fig. 1a); however, there is a great deal of very near surface variability related to heat and momentum fluxes (Fig. 1b,c). The mixed layer deepens in late winter in response to turbulent heat loss to the atmosphere. This deepening occurs because the upper water dense and results in convective instability within the water (Fig. 1c). Strong winds, usually more common in winter than in summer, can also deepen the mixed layer. In summer, oceanic heat gain from the atmosphere creates a layer of less dense water at the ocean surface, resulting in a shallower mixed layer (Fig 1b). These processes that govern the depth of the mixed layer have a big impact on how much heat the ocean actually stores. In a detailed assessment of an ensemble of 19 climate projection models run as part of the Intergovernmental Panel on Climate (IPCC) Change 4th Assessment Report, Boé et al. (2009) show models starting with deeper winter mixed layers in the 20th century result in larger oceanic uptake of heat and CO_2 through the course of the 21st century. These flux imbalances ultimately result in a cooler atmosphere (and warmer ocean) by the 2070-2099 time period.

The global poleward transport of heat, often termed the meridional overturning circulation, also depends on air-sea fluxes. In the North Atlantic, the Gulf Stream brings warm surface water northward. Wintertime air-sea fluxes create denser, colder water that sinks to mid-depth, forming North Atlantic Deep Water that returns southward. In the Southern Hemisphere, mid-depth water travels south along constant density surfaces that rise to the ocean surface within the Antarctic Circumpolar Current (Speer et al., 2000). Water that moves along these density surfaces can then warm at the ocean surface, transforming from deep water into intermediate water (e.g., Cerovecki et al., 2010). Both the Northern and Southern Hemisphere parts of this meridional overturning circulation are sensitive to the strength of the wind and the magnitude of the heat fluxes

While it is sometimes tempting to think of meridional heat transport and air-sea heat exchange as global scale processes, recent investigations suggest that they are strongly sensitive to small spatial-scale changes in sea surface temperature (e.g., Chelton et al., 2001; O'Neill et al., 2005; Cronin et al., Chelton and Xie, 2010, etc.). Major currents such as the Kuroshio Extension, the Gulf Stream, and the Agulhas Retroflection are sites of strong temperature gradients. Wind changes speed as it blows across these temperature gradients, in turn generating significant gradients in momentum and turbulent heat fluxes. Because the currents meander in space, the spatial patterns of heat and momentum fluxes also change in time. Importantly, processes contributing to fluxes interact with each other nonlinearly, and the resulting net fluxes differ from those that would be obtained from large-scale averaged fields (Josey et al., 1995, Gulev et al., 2007a,b). Similarly, orographically induced strong winds (e.g., Xie et al., 2005) can produce locally intense fluxes.

b. Sampling and Resolution Requirements

"Sampling" of a process involves more than characterizing the spatial and temporal resolutions for a given sensor. Most studies of processes important to the upper ocean, whether observation or model based, require the knowledge of several fields of variables. For example, studying air/sea exchange of heat and moisture requires knowledge of sea surface temperature, wind speed, near-surface air temperature, near-surface humidity, and surface pressure. Characterizing "sampling" based on any one of these variables is insufficient. Sampling must be described within the context of all important variables contributing to a process. Understanding sampling of heat exchange, for example, may require combining the sampling information from several sensors, many of which are situated on separate satellite platforms. Often, a satellite mission focuses on one major component of a process, such as wind speed (e.g., QuikSCAT; Graf et al., 1998). In some cases, observations from multiple satellites are used to estimate one or two of these variables (e.g., Jackson et al., 2006, 2009). One key question becomes *When are there observations sufficiently close in both space and time to estimate fluxes?* Another key question is *How often are observations required to provide sufficiently accurate estimates of the fluxes?*

The need for temporal resolution can be determined from natural variability and accuracy requirements or from the time scales of processes being examined (e.g., diurnal variability for land-sea breezes). Winds change relatively rapidly, indicating that synoptic scale variability should be well sampled; observations should be roughly daily or more frequently. Random errors on air temperature and humidity contribute to relatively large errors in fluxes, meaning that there should be sufficient sampling in space and time to reduce this random error. Enhanced spatial resolution, without substantial decrease in accuracy, can help reduce these random errors. The spatial scale of processes being examined tends to be a stronger constraint on spatial resolution, with roughly 25 km desired from most open ocean studies, roughly 5 km for most mid-latitude weather, and 1 km for near-coastal and hurricane studies.

3. Historical Challenges and Recent Improvements

Historical challenges in observing air-sea fluxes include insufficient sampling, biases, large random errors in air temperature, and no accounting for how surface water waves modify fluxes. A lack of intercalibration has also been a tremendous problem, resulting in spurious trends and variability that have more to do with the observing system than any natural processes. Intercalibration of winds and sea surface temperatures has been greatly improved in recent years. Intercalibration for atmospheric temperature and humidity is just beginning. Errors related to surface pressure are very small in comparison to other problems; therefore, improved estimation of surface pressure has had a low priority.

a. Stress

Stress, the vertical transport of horizontal momentum, is relatively accurately observed. Stress is a function of the wind vector relative to the surface, buoyancy (largely a function of the air/sea difference in temperature), sea state, and air density. Note that observations that provide only speed or magnitude (typical of most wind observations) are insufficient for most applications involving dynamics. Variability in air density is small compared to errors in the wind, air/sea temperature difference and influence of sea state. Satellite winds have traditionally been calibrated to equivalent neutral winds (Ross et al., 1985), which is like stress in the sense that equivalent neutral wind well accounts for the dependency on buoyancy. Recent studies (Bourassa et al., 2010a) have found that scatterometers, and presumably other wind-sensing instruments, respond to stress rather than wind, accounting for variability due to wind, buoyancy, surface currents (Park and Cornillon, 2001; Kelly et al., 2001; Chelton et al., 2004) and waves (Quilfen et al., 2001; Bourassa, 2006), and air density (Bourassa et al., 2010a). We anticipate that well-calibrated, satellite-derived stresses will soon be available from QuikSCAT observations. This is a tremendous advantage for improved accuracy in other turbulent fluxes because stress observations are believed to account for all sea state related variability in surface fluxes of heat and moisture.

b. Heat and Moisture Fluxes

Direct measurement of turbulent fluxes requires dedicated field experiments in which turbulence measurement can be made from in situ research vessels and buoys. This approach cannot be employed for examining the exchange over the global oceans. Instead, parameterizations have been developed that can be used to accurately estimate the turbulent exchange given “bulk,” or mean-value (nonturbulent), measurements of sea surface temperature, wind speed, and near-surface air temperature and humidity (e.g., Fairall et al., 1996). The fluxes are proportional to the wind speed (relative to the surface) times the air/sea difference in temperature (sensible heat flux) or humidity (moisture flux and latent heat flux). The proportionality is a function of wind speed and buoyancy. Two examples of satellite-estimated fluxes (Fig. 2) show great promise and demonstrate problems that remain to be solved. The patterns and magnitudes of these fluxes are reasonably consistent with expectations; however, the lack of observations in areas with rain (e.g., much of Hurricane Ivan and the fronts and core of the mid-latitude storm) show that this technique will miss fluxes in some areas where they are large and difficult to extrapolate.

The use of bulk variables allows one to estimate surface heat and moisture exchanges anywhere when all necessary variables are measured. While in situ platforms such as buoys and ships are invaluable, these represent only point measurements and they have inadequate spatial and temporal sampling over most of the global oceans. Given these inherent limitations of in situ measurements, progress in measuring heat and moisture exchange over the ocean has increasingly been made through the use of satellite-based measurements. Satellites are able to improve the spatial and temporal coverage of many of these important surface variables. However, in situ data are an essential source of comparison data for tuning and validating satellite retrieval techniques.

c. Measurement of T_{air} and Q_{air}

Latent and sensible heat fluxes are proportional to the product of wind speed (Fig. 3) and either the difference between atmospheric humidity at the sea surface and atmospheric humidity a few meters above the surface (Fig. 3) or, similarly, the difference in temperature (Fig. 3). Measurement of near-surface (approximately 10 m) air temperature (T_{air}) and humidity (Q_{air}) via satellite remains an area of intensive on-going progress. A recent comparison of satellite-based surface heat and moisture exchange products (Clayson et al., 2010) has revealed the largest source of spread between products to be rooted in Q_{air} and T_{air} retrievals rather than satellite wind speeds. Retrieval of these near-surface quantities from satellite-measured radiances is challenging. Observations in the infrared (IR) are hindered by clouds. Microwave observations are hindered by coarse spatial resolutions. Both types of observations have coarse vertical resolutions due to the nature of atmospheric retrievals. Even highspectral resolution IR sounders such as AIRS have only a 1-km vertical level output (Aumann et al., 2003). This depth can be on the order of the entire boundary layer; however, a roughly 10-meter measurement is required. Passive microwave sensors, particularly those of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I; Hollinger et al., 1991) provide yet another route to retrieval of near-surface moisture and temperature. However, many SSM/I frequencies are more responsive to the total columnar water vapor burden, or precipitable water (PW), than to a precise near-surface amount.

Earlier studies found a strong link between PW and Q_{air} on monthly time scales (Liu, 1986). Because of the strong relationship between humidity and air temperature via the Clausius-Clapeyron relationship, use of a known Q_{air} with an assumed relative humidity, usually of 80%, T_{air}, can be estimated through simple inversion of the moisture saturation vapor pressure equations; however, such estimates of T_{air} have large random errors and regional biases. While the PW-Q_{air} relationship generally holds on monthly time scales, it often breaks down for instantaneous retrievals. Further improvements have been made based upon radiative transfer studies that show certain channels of the SSM/I contain some boundary layer moisture information (Schulz et al., 1993). This has led to the production of empirical multiple linear regressions based upon collocated brightness temperatures and in situ measurements. Since these early studies, empirically based regressions have been employed as the status quo, with minor improvements (Schlüssel et al., 1995; Bentamy et al., 2003). Much less progress on the retrieval of near-surface air temperature has been made over the same period.

Recent work has sought to make improvements on the methodologies and results of these early studies. The work of Jackson et al. (2006, 2009) and Jackson and Wick (2010) improves the retrieval of both T_{air} and Q_{air} (Fig. 4) through the use of combined and single-sensor instrument retrievals. Sounding data from the Advanced Microwave Sounder Unit (AMSU-A) has been combined with the passive microwave frequencies of SSM/I in an empirical retrieval of both air temperature and humidity. The primary benefit of including the sounder data results from the ability to correct for variability higher in the atmospheric column that is not correlated to surface variations. While present sounders do not resolve well the near-surface layer, the information on moisture and temperature structure in the atmosphere complements the SSM/I data, which is sensitive to the total column amounts. However, the necessary sensors for this retrieval are on separate satellite platforms, reducing the coverage of any retrieved product because of the need for collocated footprints. The recent study of Roberts et al. (2010) has also improved upon previous retrieval algorithms (Fig. 4). Inclusion of near-surface information through a first-guess sea surface temperature with SSM/I brightness temperatures in a novel, nonlinear neural network approach has led to improved accuracies in Q_{air} and T_{air}. One great benefit of this approach is that SSM/I brightness temperatures are the only satellite-based information needed to obtain increased coverage. Examples of the SSM/I retrievals show great amounts of cold and dry air moved to the south behind the eastern storm (Fig. 4 top row) and typical tropical conditions away from Hurricane Ivan (bottom row). Multi-sensor methods for the retrieval of the near-surface air temperature and specific humidity offer potential for improvement in accuracy, but the benefits can be countered by sampling challenges.

d. Gas Fluxes

The flux of gas across the air-sea interface is commonly estimated using a bulk relationship similar to the heat and moisture fluxes. The flux is given by the concentration difference across the interface (expressed in terms of the difference in partial pressures of the gas in the surface sea water and the atmosphere above the interface) multiplied by the gas transfer velocity and the solubility coefficient of the gas. The formulation differs from that of the heat and moisture fluxes in that the combination of the exchange coefficient and wind speed is replaced with a transfer velocity. To derive the gas flux from space, both the concentration difference and transfer velocity must be estimated from satellite-derived quantities. Unfortunately, none of the needed parameters are retrieved directly by present satellites.

While methods for determining the transfer velocity have been developed for multiple gases (e.g., Fairall et al., 2000), remote estimation of concentrations and fluxes have focused primarily on CO_2. For CO_2, the primary source of variability in the partial pressure difference is the oceanic pCO_2. The variability of the atmospheric pCO_2 is much smaller both spatially and temporally and is not a major limiting factor in the accuracy of the derived flux products. Efforts to date have relied largely on broad extrapolation of available direct in situ measurements and worldwide networks (e.g., Feely et al., 2006; Olsen et al., 2004; Etcheto et al., 1999). Initial applications of infrared sounder-derived information on CO_2 concentrations higher in the atmosphere to surface flux estimates have largely been unsuccessful (Chevallier et al., 2005). Improvements in satellite-based estimation of atmospheric pCO_2 are possible through observations from the Greenhouse gases Observing SATellite (GOSAT) launched in 2009.

The oceanic pCO_2 is more variable and remote measurements are needed to spatially and temporally interpolate available direct observations. Previous efforts to map variations in surface pCO_2 have employed relationships with the sea surface temperature (SST) (e.g., Feely et al., 2006; Olsen et al., 2004; Boutin et al., 1999), SST and chlorophyll-*a* (Rangama et al., 2005; Ono et al., 2004), and recently dissolved inorganic carbon (obtained from SST, chlorophyll-*a*, and salinity) and total alkalinity (obtained from salinity) (Sarma et al., 2006). These methods, however, exhibit significant differences between regions and seasons and no clear approach has yet been identified to systematically relate variations in pCO_2 to remotely sensed parameters on a global scale. Research continues on globally valid approaches with improved accuracy.

The greatest source of uncertainty in the derived flux products lies in obtaining suitable values for the gas transfer velocity. Estimates of the air-sea flux of CO_2 have largely used simplified models based solely on the wind speed (e.g., Wanninkhof, 1992). Uncertainty exists as to the appropriate relationship to wind speed: both quadratic (Wanninkhof, 1992) and cubic (Wanninkhof and McGillis, 1999) relationships have been used. These simplified models fail to capture all the processes influencing gas transfer. Surfactants, rain, microscale wave breaking, and biological process may significantly affect the gas transfer, particularly at lower wind speeds. Present work is focused on developing approaches that better capture these dependencies.

The greatest sensitivity of the derived transfer velocities is to variations in the wind speed. The results in Fig. 5 show global monthly averaged estimates of the CO_2 transfer velocity and associated uncertainties computed using the model of Fairall et al. (2000). Note that nearly 95% of the uncertainty is contributed by errors in estimating the wind speed. The next largest contributor is the SST. Based on these results, the wind speed must be measured to an accuracy of ~ 1 m/s to provide a 20% uncertainty in k. This places strong requirements on the procedures used to grid and average the wind speed. The total uncertainty at wind speeds above ~ 15 m/s is still largely uncharacterized because of a lack of observations and an incomplete understanding of the role of bubble processes.

Two approaches for estimation of gas transfer velocities derived solely from satellite observations have been developed. One approach uses the COARE V3.0 bulk flux algorithm (Fairall et al., 2003) and satellite-based estimates of the input parameters (Jackson and Wick, 2009). The other approach attempts to directly relate the transfer velocity to variations in the ocean surface roughness, thereby simultaneously accounting for the wind speed, sea state, and relevant biological processes. Details of the application of this technique using altimetric data are provided in Frew et al. (2007) and

Glover et al. (2007). Recent work by these investigators has extended the technique to the use of scatterometry data, providing enhanced global coverage.

4. Goals for the Future Observing System

There are several considerations key to improving the accuracy of satellite-derived surface turbulent fluxes. Coincidentally, the requirements for these improvements will also improve the accuracy of radiative fluxes, which are sensitive to the amount of water vapor in the atmospheric boundary layer. The key considerations are validation and intercalibration, determining the needed sampling and resolution required to achieve desired accuracy, and conducting more detailed process studies to determine the accuracies required for various applications.

We need more in situ observations outside of the tropics and away from coasts (or with sufficient resolution to work near coastal buoys). Air temperature and humidity retrieval would greatly benefit from data over cold water, a condition that is poorly sampled with the historical observing system. TAO/Pirata/Rama buoys cover the tropics, but relatively few measurements are made outside of the tropics. Exceptions include the KESS and Climode flux moorings and the planned Ocean Sites network. Argo floats don’t measure atmospheric variables, and surface drifters have relatively poor accuracy and spatial sampling when they do so. The traditional routes of Volunteer Observing Ships (VOS) don’t cover large portions of the ocean (i.e., Southern Ocean). Research vessels offer an alternative source of relatively high quality data (due largely to the practice of recording data at rates of one observation per minute or better). The Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative has made excellent progress toward providing quality-assured data from many US-based research vessels in near real time. Similar processing of data from select older cruises (e.g., those of the Antarctic support vessels L. M. Gould and N. B. Palmer) would be extremely useful for global calibrations that are applicable to high latitudes. An important goal is to obtain observations from high wind speed (> $18 ms^{-1}$) conditions, which are quite rare but are associated with very large fluxes, important oceanic and atmospheric processes, and hazardous operation conditions. Lastly, spurious trends due to changing calibration characteristics are more likely to be identified and corrected if there is periodic comparison to in situ observations.

Long-term climate data records invariably rely on combining instrument records from separate platforms. Individual satellites have unique fields of view, footprint size, sampling, and error characteristics. Combining these records can easily cause erroneous trends in the resulting climate data record. These problems can be reduced if the satellite missions of similar observations overlap. It would also be useful to have different types of instruments measuring the same parameter very closely collocated in space and time. For example, instruments flown on the same satellite or in series of satellites closely space satellites in the same orbit (e.g., the A train). For rapidly changing variables (such as wind), this approach would enable a much better understanding of the differences between such instruments. Reduced sampling is a serious downside to this approach to improving calibration.

Process studies are needed to determine accuracy requirements for surface turbulent fluxes. A survey of scientists studying high-latitude processes revealed that accuracy requirements were often poorly known, and only crude estimates could be provided for most processes (Bourassa et al., 2010c). Very long term processes require biases of < $1 Wm^{-2}$, which are not achievable with today's observing system. Resolution requirements for small scale processes (requiring fine spatial and temporal scales) might not be consistent with global requirements, which require sufficient sampling over all the global oceans. The most fruitful way forward might be to continue ongoing missions (e.g., programs for AMSR, AMSU, SSM/I, and scatterometers) for global coverage of turbulent fluxes and to add a few specialized missions that not only can contribute to global coverage and improved temporal sampling, but also provide finer spatial resolution needed for many process studies (e.g., the Duel Frequency

Scatterometer (DFS) or the eXtended Ocean Vector Wind Mission (XOVWM) scatterometer). Vector wind or stress data is often highly desirable for such process studies, and the derived ocean transport is often important.

Techniques are being developed to provide a wealth of surface turbulent flux information from satellites. The accuracy of surface fluxes calculated with the current observing system is yet to be comprehensively determined, yet it is known sampling of vector winds (or stress) is insufficient for many applications. Maximum benefit of the satellite observing system can be achieved through international collaboration on data sharing, orbit planning (i.e., temporal sampling), in situ calibration, and intercalibration.

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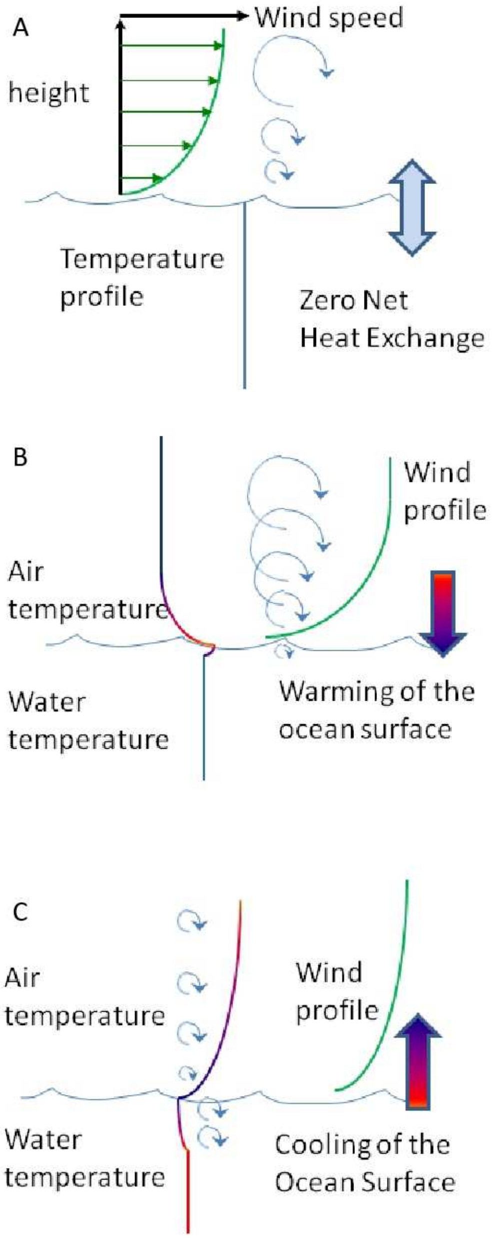

Figure 1: Changes in temperature of the ocean surface can cause large changes in the surface turbulent fluxes. If there is no heating or cooling of the ocean surface (top), all the ocean mixing near the surface is due to winds and waves. If the surface warms (middle), the atmospheric boundary layer becomes more unstable, enhancing mixing and fluxes in the atmosphere. In contrast, the ocean becomes more stable, reducing mixing, and trapping the energy near the surface. If the ocean surface cools (bottom), mixing in the ocean is enhanced, and turbulent fluxes in the atmosphere are decreased.

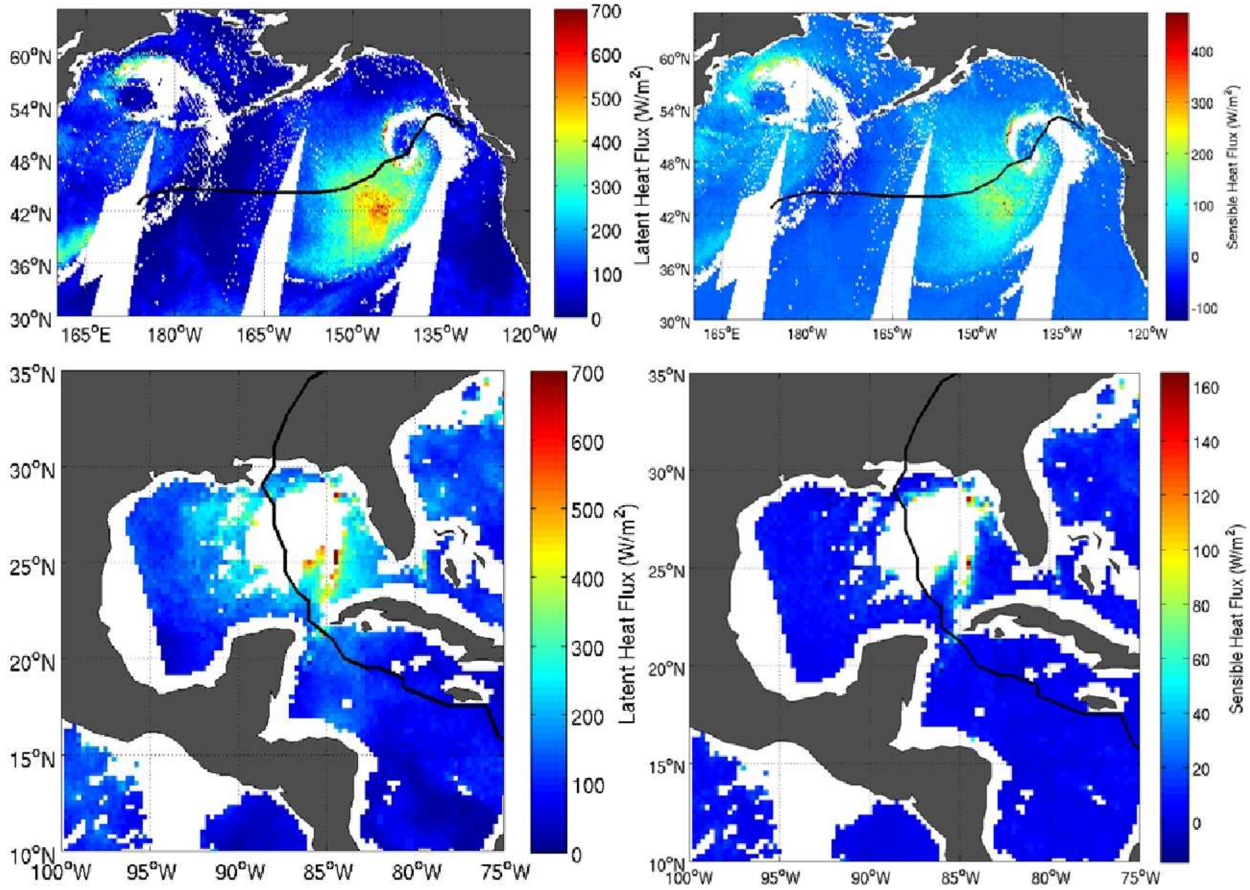

Figure 2: Satellite-based estimates of the latent heat flux (left column) and sensible heat flux (right column) for an intense mid-latitude storm (top row) and Hurricane Ivan, 2004 (bottom row). Missing values occur where there was too much precipitation, masking out much of the interesting area for hurricanes, but much less of a problem for fluxes behind mid-latitude storms.

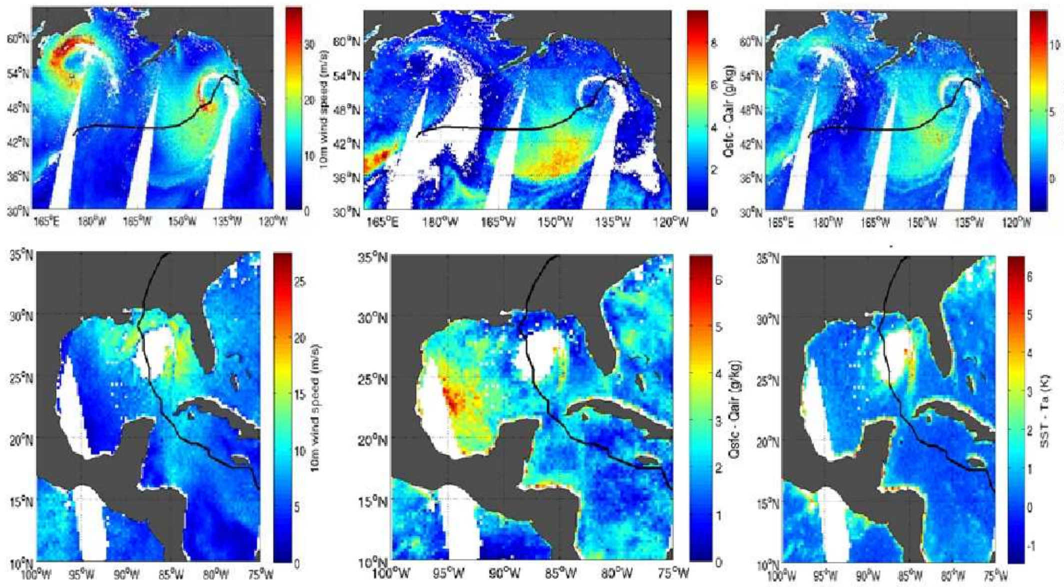

Figure 3. Wind speeds (left column), air/sea differences in humidity (middle column) and air/sea differences in air temperature (right column) for the same cases as in Fig. 2. The fluxes are proportional to these wind speeds and differences. The wind speeds are from Remote Sensing Systems v6 SSMI product.

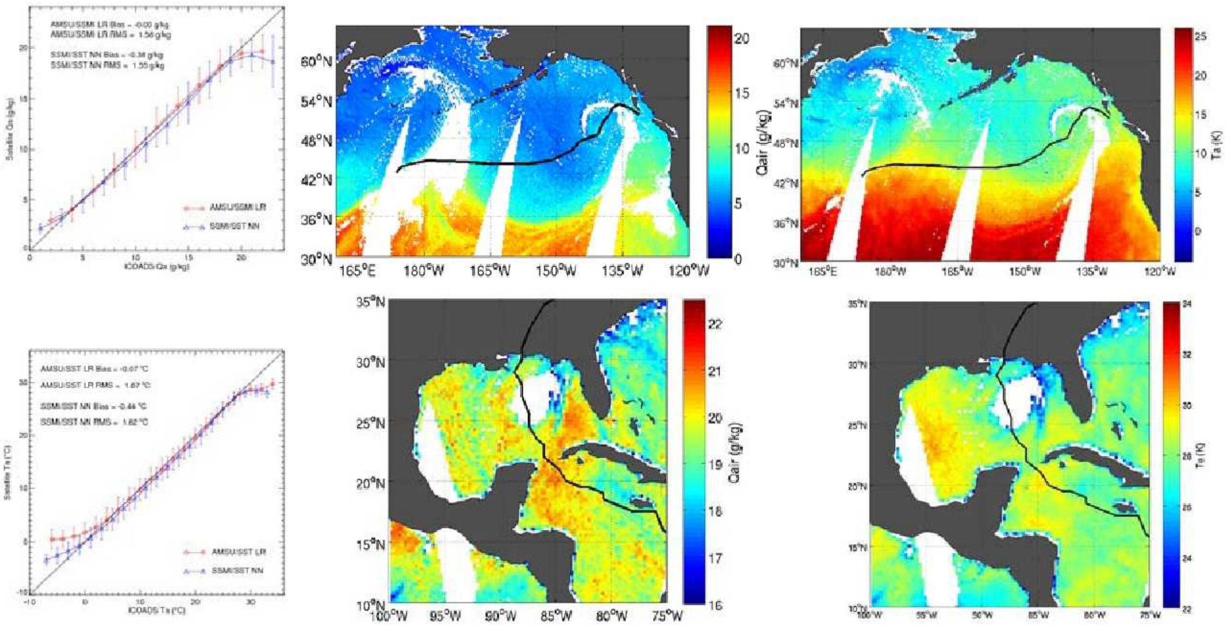

Figure 4. Validation of satellite retrievals of humidity at a height of 10 m above the water surface (top left) and air temperature at the same height (bottom left); and examples of humidity (middle column) and air temperature (right column) for the same cases as in Fig. 2.

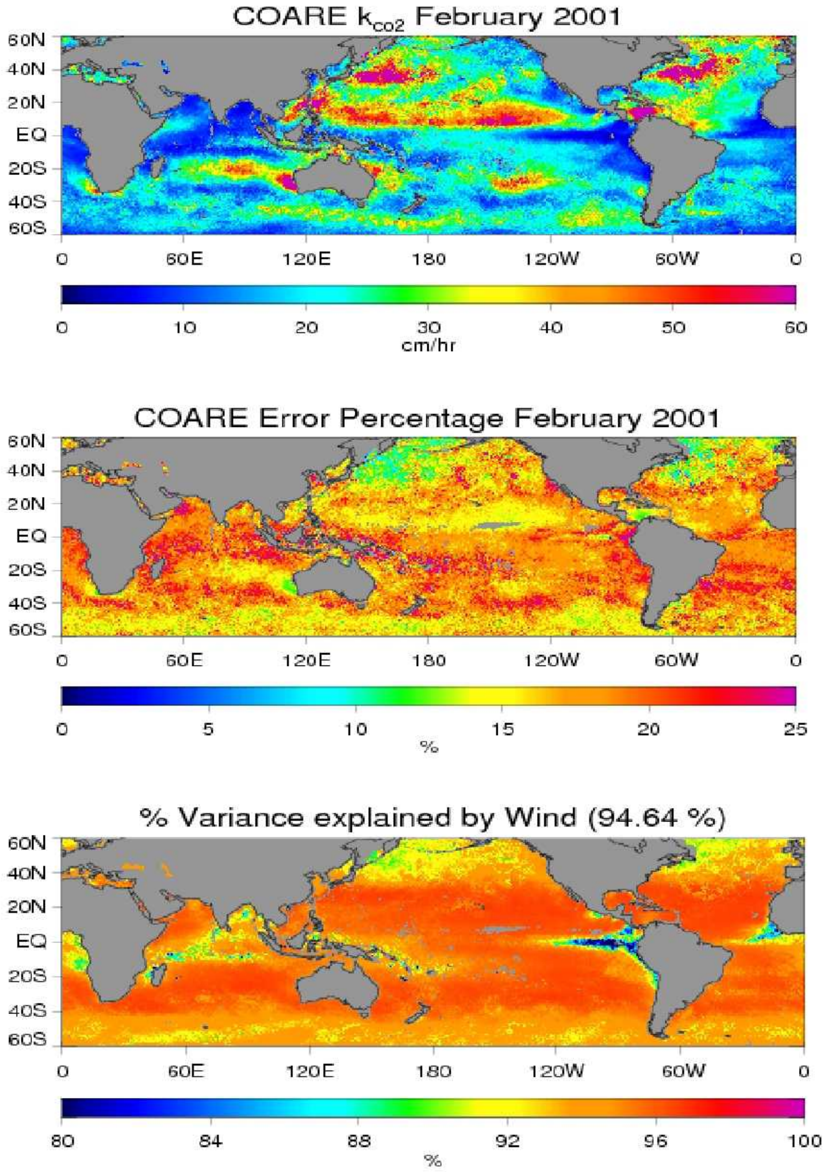

Fig. 5. Modeled CO_2 gas transfer velocity and associated uncertainty. The upper panel shows the monthly averaged CO_2 gas transfer velocity for February 2001 computed using the Fairall et al. (2000) model. The corresponding estimated uncertainty expressed as a percentage is shown in the middle panel. The lower panel shows the fraction of the uncertainty due to uncertainty in the measured wind speed as a function of location.